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GIS HYDROLOGICAL MODELING IN AN AGRICULTURAL RIVER BASIN WITH HIGH POTENTIAL FOR WATER EROSION

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Abstract

This paper presents a study on the use of GIS technology in determining the leakage caused by water erosion in a river basin of 370 ha. The research presented in this paper is carried out in the Sulita hydrographic basin from Botosani County.
The main objective is represented by the spatial analysis of the processes that take place in the hydrological system and of the physical-geographical factors that determine their variability. This GIS system developed under ArcGIS 9.2 can be considered a basic research in structuring a hydrological GIS and in creating an appropriate geospatial database.
The approached method is based on the digital analysis of the terrain, determining the morphometric parameters and the hydrological parameters. Using the ArcGIS 9.2 software, the calculation of slopes and directions is done at the pixel level, in a 3x3 pixel window, on all 8 directions from the central pixel to the neighborhoods. The important part of the paper is the determination of the parameter called flow accumulation, which in the study of water erosion, that indicates the way in which the actual flow is carried out on the slopes.

Key words*: Database, water erosion, GIS, hydrological modelling.*

INTRODUCTION

The alluvial stream on the slopes as a result of the erosion processes carried out at the level of the slopes and of the riverbed network is a very complex process that depends, on the one hand, by natural factors, and on the other hand by a series of human activities.
Globally, erosion is one of the greatest problems of humanity, vital to the process and its economic stability, to the environment. Of the total fertile soil reserves of the Earth (approx. 3.5 trillion tons), 23 billion tons are eroded annually; at this rate, the soil reserve can be depleted in 152 years (Rusu et al., 2020).
According to U.S. Department of Agriculture (USDA) data, in recent decades, erosion of humus over its ability to form has affected 1/3 of the globe's arable land.
The volume of sediments with a high percentage of nutrients from eroded soils transported by rivers and oceans has increased globally from 9 billion t/year, before the intensive cultivation of soil and irrational overgrazing, to 24 billion t/year (Chiorascu et al., 2017; Cojocaru et al., 2016).
In Romania, out of the total agricultural area (approx. 15 million ha), 44% is located on slopes of over 5% (usually lands with a slope below 5% are considered without danger of erosion). If only arable land is mentioned, out of the 9.8 million ha, 35% are located on slopes of over 5% (Niacșu, 2015).
The most important problem facing agriculture in Romania is soil erosion. This process of degradation (pollution in modern ecological conception) is extended to almost half (47%) of the agricultural surface of the country, respectively on approx. 7 million ha, representing the lands affected by the degradation process, of which 6.75 million ha of eroded lands (including 0.25 million ha of active landslides) and 0.25 million ha are lands with wind erosion. Of the 7 million ha mentioned, 3.9 million are lands with appreciable erosion, but with the danger of erosion if no vigorous measures are taken to control them and 3.1 million ha of lands affected by moderate to very strong erosion processes. Water erosion predominates (95.7%). 150 million tons of soil are lost annually due to erosion, containing 1.5 million tons of humus, 0.45 million tons of soil with nitrogen, as well as significant amounts of phosphorus, potassium and other nutrients (calcium, magnesium, zinc, molybdenum,

boron, etc.). The specific annual soil losses due to erosion vary between 3.2 and 51.5 t/ha; the weighted average in Romania being 16.28 t/ha year, much higher than the maximum allowable tolerable losses of 3-6 t/ha year (Rosca et al., 2015).

The applicability of Geographic Information Systems (GIS) methods and techniques in the field of Hydrology is extremely diverse, ranging from determining the morphometric parameters of river basins, to the ability to solve deterministic, process-based models, or even distributed models.

Society's progress is also closely linked to the ability to store, process and interpret information based on mathematical algorithms used in spatial analysis, given the explosive growth of data and the need to make decisions in the shortest possible time. Geographic Information Systems emerged as a consequence of this progress, based on the simplification of the real world by its representation in the form of layers, which facilitated the analysis of spatial variables and the distribution of entities on the earth's surface.

The rapid development of this field (as well as all computer technologies) and the widespread use of computers and modern measurement techniques (automatic stations, radars, satellites, drones, etc.) have allowed the development of calculation methods and algorithms and, further on, mathematical models and applications in the GIS environment. All this has led to the use of GIS in the field of modelling and hydrological analysis, by expanding the spatial analysis and detailing the physical processes that take place in the hydrological system (Irimuș et al., 2017; Niacsu et al., 2015).

MATERIALS AND METHODS

Research area

This paper describes a research conducted on a land with an area of 370 ha, i.e. the V-Sulița perimeter in Botoșani County, Romania (Figure 1). From the administrative point of view, it is in the Sulița and Lunca communes. From the hydrographic point of view, the V-Sulița perimeter is located in the Sitna river basin, which is part of the Prut river basin. From the geomorphological point of view, the area studied is located in the Moldavian Plain, the Jijia-Bașeu depression.

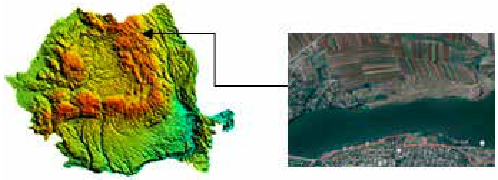

Figure 1. Location of investigated area (https://earth.google.com)

The relief is represented by differently exposed slopes, plateaus and valleys. For the climatic characterization of the studied area, we used meteorological rainfall data from Sulița station located within the perimeter, while the other data were collected from Botoșani station, located about 25 km away. The land in the investigated perimeter is affected by surface erosion processes, the steep slopes are sometimes affected by deep erosion materialized in ditches, gullies and ravines. Also, where coastal springs are present and the solidification rock is represented by marl and/or clay, there are active and semi-stabilized landslides. For the pedological characterization of the analysed perimeter, the studies prepared at the Botoșani County Office of Pedological and Agrochemical Studies were used, based on which the pedo-amelioration sectioning was achieved depending on the intensity of the limitations of agricultural land use or the possible risk of degradation and subclasses depending on the nature and extent of limitations.

Research method

With the improvement of information technology, the performance and capabilities of GIS have expanded, evolving from simple software applications to crystallization, in the opinion of many specialists (Haidu et al., 2012), as an independent field (even if the tools they operate with are borrowed from other fields), (Moldovan et al., 2019).

The applicability of GIS methods and techniques in the field of Hydrology is extremely diverse, ranging from determining the morphometric parameters of river basins, to the ability to solve deterministic, process-based models, or even distributed models (Cochrane et al., 1999).

For the evaluation and modelling of leakage, modern methods specific to GIS, but also those of aerial photography and remote sensing play an important role.

They complement the field of hydrology, allowing, on the one hand, the organization, visualization and, especially, the processing and analysis of spatial data, and on the other hand, the increase of the performances of hydrological models.

The most eloquent example is the topological modelling of the river basins and the translation, on a space scale, of the applicability limit between the systems with concentrated, semi-distributed or distributed parameters (Figure 2).

This type of approach takes into account the non-uniformity in space of the conditional factors of the flow (topography, lithology, vegetation, soils, etc.), as well as the non-uniformity in time and space of precipitation, and involves the division of the basin and the hydrographic network into homogeneous units, followed by the modelling of the rain-runoff process (Bilaşco et al., 2018; Teresneu et al., 2021).

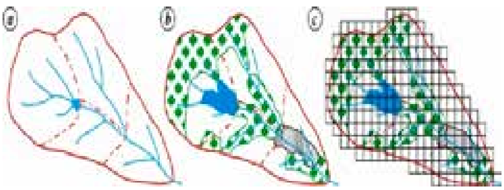

Figure 2. Topological modeling of river basins:
a) system with concentrated parameters; b) system with semi-distributed parameters; c) system with distributed parameters, (Bilaşco et al., 2018)

Both the input data in a GIS and the information resulting from the processing and analysis have as main characteristic the spatiality or georeferencing, which means that each element of the map is linked to a certain place, to other computer systems (Biali et al., 2020; Haidu et al., 2012; Moore et al., 1992).

Morphometric parameters of the terrain

The morphometric parameters of the terrain also called primary parameters are of particular importance in any study involving the modelling and assessment of erosion processes and phenomena on slopes.

In this project DEM's has a spatial resolution of 25 m, it was created in 2020, by the Kriging interpolation method.

Slope

It is commonly perceived as the magnitude of the increase in altitude with the distance in the direction in which it is greatest, and is usually calculated by reference to a fixed distance, 100 meters, for example. If the distance in the plane is considered, the ratio between the altitude difference and the distance travelled is the tangent of the angle between the earth's surface and the horizontal of the place. If the distance on the earth's surface is considered, the slope becomes the sine of the same angle. The difference between the two is not significant for a slightly sloping surface, but it is very large for very sloping surfaces.

In the program developed under GIS application, the value of the tangent is used and expressed as such, the value of the ratio (calculated for a distance of 100 meters, and expressed as a percentage), or by the value of the angle of the surface with the horizontal.

For a continuous, analytic surface, S (X, Y) = Z slope represents the first-order derivative of the function S (eq.1), thus:

$$S=\sqrt{\left(\frac{\partial Z}{\partial X}\right)^2+\left(\frac{\partial Z}{\partial Y}\right)^2} \quad (1)$$

This formula implies the possibility of determining the variation of the altitude on very small, infinitesimal distances. In a GIS, however, surfaces are not analytical but are modelled by irregular triangular grids or rectangular matrices with a finite resolution. That is why the calculation formulas implemented in various GIS applications are approximations of it, which are applied on grids (Cochrane et al., 1999).

In ArcGIS, the slope is calculated according to an algorithm that takes into account all 8 points in a 3 x 3 pixel neighbourhood (Figure 3), around the point where the calculation is desired. This is the finite difference method (FD) (eq. 2 and eq. 3). For example, for the pixel P in the adjacent figure, the slope will be calculated by applying eq. 1, but considering:

$$\frac{\partial Z}{\partial X}=\frac{(Z_{NV}+2Z_{V}+Z_{SV})-(Z_{NE}+2Z_{E}+Z_{SE})}{8\Delta X} \quad (2)$$

$$\frac{\partial Z}{\partial Y}=\frac{(Z_{NV}+2Z_{N}+Z_{NE})-(Z_{SE}+2Z_{E}+Z_{SV})}{8\Delta Y} \quad (3)$$

where Z is the altitude value, and ΔX and ΔY are the resolutions on the X and Y axes (in the case of the study equal to 25 m).

NW	N	NE
V	**P**	E
SW	S	SE

Figure 3. A neighborhood of 3 x 3 pixels for the central pixel P

Land exposure

The land exposure is an element of natural potential that can be used in various applications, for example:

- finding all the slopes with southern and western exposure to determine the best areas to cultivate but also which have high potential for erosion;
- finding all south-facing slopes to identify the places where snow is most likely to melt first, as part of a study to identify areas exposed to flooding.
- estimation of incident solar radiation, as part of a study to determine biodiversity in different sites;

In ArcGIS, the function for determining the exposure values is applied analogously to the one for determining the slope, also on the same neighborhood of 3 x 3 pixels, and the formula (eq. 4), which is applied for each pixel in part it is:

$$A=\frac{360}{2\pi}\cdot\arctan\left(\frac{\partial Z}{\partial Y},-\frac{\partial Z}{\partial X}\right) \quad (4)$$

Where the function $\arctan\left(\frac{\partial Z}{\partial Y},-\frac{\partial Z}{\partial X}\right)$ applies to both slope components determined by eq. 2 and eq. 3.

Hydrological parameters of the terrain

The distribution of the altitude in space directly determines the flow, and the water is the main modelling agent of the slopes. Hence, the concept of morpho-hydrographic basin as a basic unit of the natural geomorphological system. Extracting as much information as possible from an altitudinal numerical model, necessary for a hydrological analysis, has been an active concern in the scientific community, and the algorithms that have been developed for this are numerous and offer different results. The methods by which hydrological parameters are extracted from a Digital Elevation Model (DEM) fall into two broad classes: those that consider flow to and from pixel centres (also called flow-routing algorithms) and those that consider free flow to any direction (also called flow-tracing algorithms). The first methods are applied in the context of the D8 approach (all 8 pixels in the 3x3 neighbourhood of the pixel for which it is applied are considered) and are included as standard in most GIS applications and the latter are more elaborate, involve more complex functions and have some restrictions of use (Cojocaru et al., 2018). A distinction is also made between one-dimensional and two-dimensional flow.

RESULTS AND DISCUSSIONS

Digital terrain analysis

This stage involves deriving some parameters of the terrain from the numerical altitude model and analysing their distribution by cartographic methods (maps, profiles, block-diagrams) and statistics (frequency histograms). These are differentiated in (Bilasco et al., 2017): primary parameters, derived directly from the altitude values of the DEM, such as slope, exposure and curvature and secondary parameters, obtained by combining one or more primary parameters and which serve to describe geomorphological processes, such as stream power index (SPI), stream power deficit on basin slopes (DEBAS), Melton Ruggedness Number, (MRN) (Teresneu, 2019).

In the present study, we adopted the method that classifies the terrain parameters according to the purpose of the analysis in (Biali et al. 2021; Niacsu, 2012):

1) morphometric parameters, which describe the morphology of the surface,
2) hydrological parameters, which describe the leakage potential of the material, and therefore the risk of erosion, and

3) climatic parameters, climate variables adjusted to relief (Moţoc, 2002).
This is represented the hypsometric map in Figure 4 and Figure 5 (different perspective).

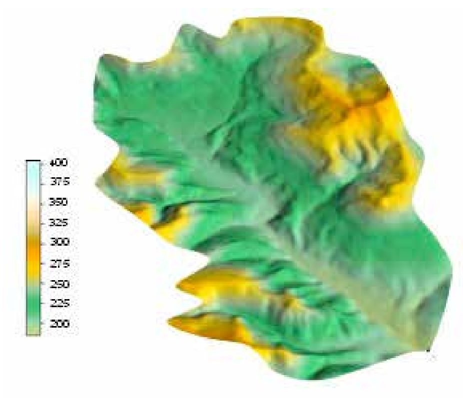

Figure 4. Representations of the Sitna basin, based on the numerical altitudinal model (DEM's) - perspective 1

The hypsometric map is performed by classifying the range of altitude values into classes that correspond to limits defined by the architect of the GIS system or limits to the development of natural processes

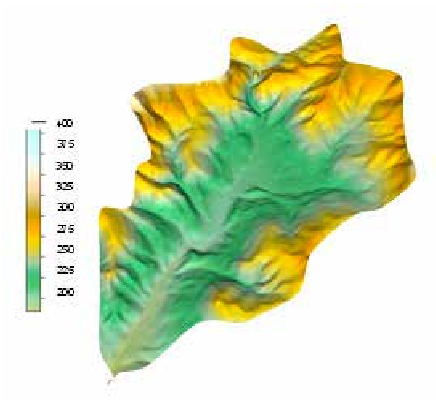

Figure 5. Representations of the hypsometric map in Sitna basin, perspective 2

Morphometric parameters of the terrain

Slope

The slope is the indicator that best estimates the action of gravity, being the means by which it controls the flow of water. It is therefore particularly important for geomorphological processes, which can accelerate or fade depending on certain threshold values of the slope. The slope also controls the hydraulic gradient, which can be decisive in the hydrogeological processes.

In ArcGIS, the slope is calculated according to an algorithm that takes into account all 8 points in a 3x3 pixel neighbourhood, around the point where the calculation is desired. This is the finite difference method (FD) (Biali et al., 2020).

Applying this algorithm with the Slope tool of ArcGIS 9.2. the map was obtained in Figure 4, in which the slope values, in sexagesimal degrees, are classified into five ranges and represented in different colours (Figure 6). An immediate application of a GIS is the possibility to generate the histogram for the respective slope classes (Biali et al., 2021).

This provides useful quantitative information in analysis.

For example, in the case of this paper, it is observed that the largest areas also have the largest slopes, over 10%, while the lowest values of the slope are concentrated in the depression areas.

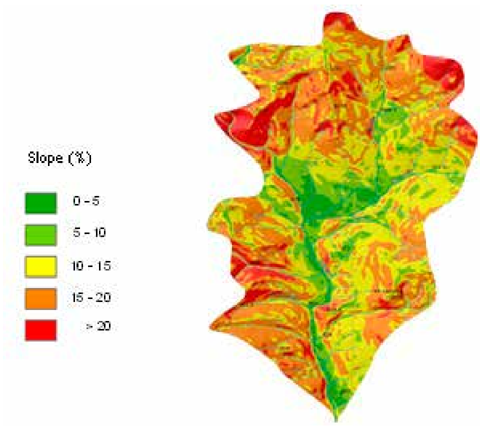

Figure 6. Map of the slopes in the studied river basin

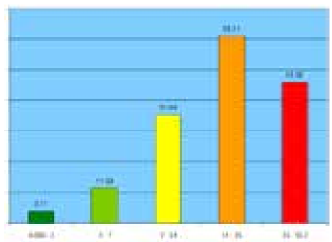

Figure 7. Histogram of the slopes in the studied river basin

In the resulting histogram (Figure 7) it can be determined that the surfaces with different slopes: slopes 15-20% predominate with 47% from area, slopes over 20% on 29% from area and slopes between 10 and 15 occupy 23% of the studied area.

Drain direction/Land exposure

Previously it was shown that the slope is elevation changing with distance. This variation is a vector because it is measured in a certain direction, namely the one in which it has the maximum value (Biali et al., 2018). The slope is the size component of the gradient vector, and the direction is expressed by the exposure of the slopes. This is the angle, in sexagesimal degrees to the north, of the slope line.

Usually, the resulting map is already classified by the algorithm that makes it, in the directions to the cardinal points: N, NE, E, SE, S, SW, W and NW (Figure 8).

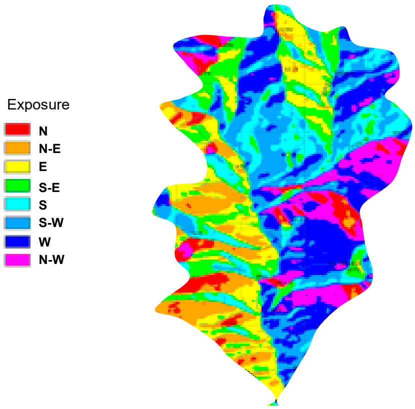

Figure 8. Slope exposure map

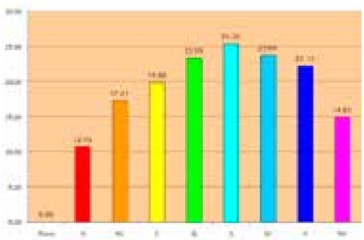

Figure 9. Histogram of slope exposure classes

In the resulting histogram (Figure 9) it can be determined that the surfaces with southern exposure predominate: S, SE and SW are predominant exposures of the slopes, which means that they are sunny slopes, with warm soils, so with agricultural potential. This fact can be important in the modelling of climatic parameters and vegetation.

Hydrological parameters of the terrain

The numerical altitude model is a rectangular matrix of altitude values. Each value is represented graphically by a pixel of a certain colour. Hydrological parameters are also represented by rectangular matrices of values, grids that overlap spatially on the altitude matrix. In other words, each pixel of altitude will correspond to the value of the calculated indicator. They are calculated based on the principle that flow always occurs from a higher altitude pixel to a lower altitude one. Basically, the problem is to determine, for each pixel separately, the number of all the other pixels that "pour" into it, which have higher altitude values and which is connected by this virtual flow of water (Figure 10).

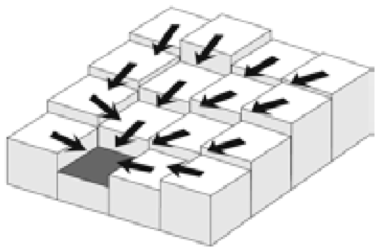

Figure 10. Drain calculation scheme
(Arc/Info Data Management, 1994)

Multiplying this number of pixels with the size of the surface of each of them (with the square of the resolution) an important hydrological indicator is obtained which has the size of a surface, but which must be associated with water flow: the surface of the basin upstream (upslope catchment area), also called the accumulation of flow (flow accumulation). If, for the respective basin, the precipitation values are known, either from concrete data, for example recorded after a rain, or entered as test values, expressed in mm, and multiplied by the surface of the basin upstream, a distribution of an indicator is obtained which has the unit of measurement of a volume of water, expressed in cubic meters.

If we consider the altitude values of the pixels that contribute to the flow towards a certain pixel are considered, two other hydrological indicators are obtained the average altitude of the basin (upslope catchment height), as an average of the altitude values of the contributing pixels and the average slope catchment slope, as the average of the slopes calculated for each contributing pixel (Figure 11). Values represent the average slope for the pixels that contribute to the flow, in degrees.

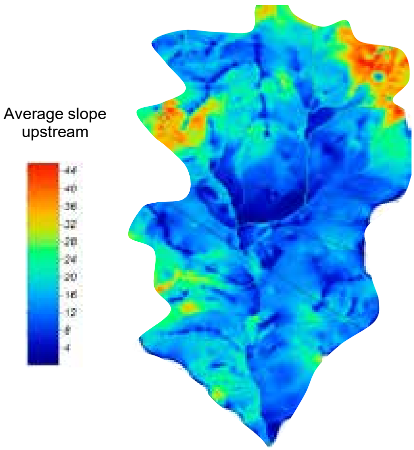

Figure 11. Average slope upstream

CONCLUSIONS

In this paper the aim was to present methods for calculating and representing the spatial distribution of some terrain indicators. The selected indicators are the most used in geo-morphometric studies, in hydrological and climatic models, and their distribution offers a broad picture of the natural potential of a region.
The spatial resolution is chosen depending on the size of the study area, the available data set. The results of the simulation and the study are directly influenced by the choice of resolution, the higher the resolution (i.e., small-sized pixels), the better and more accurate the results.
The morphometric parameters of the terrain are the slope, the exposure and the length of the slopes. These are the primary parameters that underlie the determination of all others, so their derivation is a very important operation.
The hydrological parameters are derived from the altitudinal numerical model also based on morphometric parameters: the slope and accumulation of flow (or the surface of the basin upstream), and describe the potential of the relief to influence the flow. Also, by including precipitation data and soil characteristics, they can be used to quantitatively estimate water erosion in the river basin during a rainfall (e.g., flow accumulation can provide the size of the water flow in each pixel of the model).
The GIS technique in this research made it possible to map surfaces with a risk of water erosion. This study showed that 43% of the surface of the river basin is with a very high to excessive erosion potential, 37% of the surface with a high to medium potential and 20% with minor erosion potential. If the current map of land use was to overlap with this mapping, we could determine the arable areas (or of any category of use) vulnerable to water erosion. If the soil map overlaps this mapping, we could make a connection between the accumulation of flow and the characteristics of the soils that can be subjected to water erosion.

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